The Plynlimon water balance 1969-1995: the impact of forest and moorland vegetation on evaporation and streamflow in upland catchments

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Abstract

The Plynlimon experiment in mid-Wales, designed to determine the extent to which coniferous plantation increases evaporation losses and reduces streamflow relative to upland grassland, has now been yielding data since 1969 from the grassland Wye and the 67% forested Severn catchments. Water balance analyses of the early data indicated significantly higher evaporation rates from the forested catchment and studies of the hydrological processes involved attributed this to the high loss rates of precipitation intercepted by the forest canopy. Models based on these process studies predicted losses from the forested catchment that were similar but marginally higher than those determined by the catchment water balance.

As the data sets from the catchments increased in length and a detailed reassessment of the ratings of the streamflow gauging structures was completed the updated water balances continued to show a significantly greater evaporation loss from the forested catchment, but the gap between the forest water balance and the model predictions widened. Furthermore Hudson and Gilman (1993), using the best data sets then available, identified downward trends in the evaporation from both catchments which the models did not reproduce and for which no obvious physical or physiological explanation was forthcoming.

This dictated a major reassessment of the longer data sets, using the more powerful data processing techniques now available, to identify and eliminate any errors and inconsistencies. This paper describes the reassessment of the precipitation data and the estimates of potential evaporation and presents the water balance results emerging from the revised data sets.

The revised results indicate that the evaporation losses from the grassland Wye catchment remained broadly similar to the potential evaporation estimates throughout the 1969–1995 period. The losses from the forested area of the Severn catchment declined from a level some 61% above that of the grassland in 1972 to a level only 18% higher *before* the start of felling in 1985. This downward trend continued as the felling and re-planting progressed. Over the period since 1990 the forest catchment losses appear to have stabilised at some 5–10% below those of the grassland catchment.

Using the revised precipitation and potential evaporation data, process based models over-predict the forest catchment evaporation throughout the period and do not mirror the pre-felling decline. Possible reasons for this apparent decline in evaporation rates are discussed.

Introduction

The Plynlimon experiment was set up in mid-Wales in the late 1960s to assess the impact of the dominant, contemporary land use and vegetation change in the uplands, from indigenous moorland or sheep pasture to coniferous forestry, on the quantity and time distribution of streamflow. The experiment was designed to test, at the catchment scale, the hypothesis of Law (1956) that planting of coniferous forests in moorland catchments increases evaporation rates and reduces streamflow, and that the reduction in usable water resources results in considerable economic cost to the Water Industry as well as having water quality and ecological impacts.

In assessing the economic and water resource implications of afforestation, quantifying the extent and persistence of hydrological changes has always been as important an objective as simply proving that a difference exists. A rigorous experiment was needed to quantify the land use effects, using larger representative catchments, the upper Wye (10.55 km^2) and upper Severn (8.7 km^2), than had been the case with Law's small lysimeter experiment. Within ten years, the Plynlimon experiment was able to demonstrate that evaporation from typically forested areas in the wet and windy uplands of Britain (Calder & Newson, 1979) was approximately double that of moorland areas. The extent of the change in evaporation was from a characteristic 15–20% of rainfall in moorland areas to 30–40% in 'mature' forested areas.

This range of possible values for forest evaporation reflects the different results obtained from plot studies (Calder, 1976; 1977) and the catchment experiment (Kirby *et al.*, 1991; Hudson *et al.*, 1997a). This is not an indication of deficiencies in either method; it simply illustrates the different interpretation that must be put on results from studies conducted on small, carefully-selected plots (c. 0.01 ha) and from catchments of c.1000 ha that will be subject to considerable internal spatial variability in processes as well as complex catchment integration effects. The conclusions from process studies of forest evaporation conducted within the Plynlimon catchments have generally agreed with the catchment results in direction of change, but invariably the catchment experiment indicates lower rates.

To assess and explain impacts at the catchment scale, requires an evaporation modelling approach (Hall & Harding, 1993) based on the physical principles identified at the process scale and calibrated by the integrated fluxes measured at the catchment scale. First, however, it is necessary to establish the magnitude of these catchment fluxes and to define the framework of spatial and time variability that will guide the future direction of process research. Since early analyses established the clear hydrological differences between forested and moorland catchments (Kirby *et al.,* 1991), the variability in climate conditions experienced over the study period introduced the possibility that the combined hydrological response of the catchment and the physiological response of the vegetation might vary with climate and with the degree of forest maturity, and that this intrinsic variability should be taken into account in hydrological models. Climate change may be a controversial issue; nevertheless, variability in both the short and long term is to be expected. Long-term, worldwide climatic data (see for example Houghton *et al.*, 1990) have highlighted the existence of cycles of various frequencies; they have also indicated tentative trends in some variables, particularly in temperature and rainfall (Cole *et al.*, 1991) that must have an impact on hydrology.

Hudson & Gilman (1993), using the then best estimates of water balance fluxes, detected a decline in evaporation from both moorland and forested catchments at Plynlimon over the period 1972–1987; this could be explained only partly by changes in atmospheric demand as indexed by the Penman (1948;1949) estimate of potential evaporation. Several possible explanations were suggested for this decline in evaporation, including anthropogenic effects from increasing CO_2 concentrations (Idso & Brazel, 1984), and increasing temperature and its effect on climate and rainfall amounts and distribution. However, some doubts still remained over the accuracy of estimation of hydrological fluxes in upland catchments, especially precipitation inputs and estimates of potential evaporation. It was felt that these needed to be addressed in the light of the extended data set now available (1969/1972–1995), and an increased awareness of the possible controls on evaporation gained through process studies. To complete the picture for the whole forest rotation, (as reviewed by Bosch & Hewlett, 1982) the onset of felling of mature trees in the Severn catchment that started in earnest in 1985 has been considered and the Plynlimon study has been linked with experiments at Coalburn (Robinson, 1986; Robinson *et al.*, 1998) and at Llanbrynmair (Hudson *et al.*, 1997) dealing with the initial afforestation to canopy closure phase of the forest cycle.

Evaporation in the Uplands

Evaporation from upland vegetation is a combination of biological transpiration and interception loss, the direct drying of the canopy after rainfall. Many process studies (Calder, 1976, 1977; Roberts, 1983) have suggested that transpiration is a conservative process driven mainly by incoming solar energy but limited by the feedback mechanisms of soil moisture limitation, and stomatal closure when the canopy is wet. The result is that evaporation rates from grassland, and also from forests in low rainfall climates, tend to show less year to year variation than precipitation or streamflow.

In contrast, interception loss, which is important in tall vegetation such as forests that have aerodynamically-rough canopies, depends not only on energy inputs, but also on the length of time that the canopy remains wet. This in turn depends on the amount and distribution of rainfall and, especially, on the frequency of coincidence of high vapour pressure deficits and wet canopies. In forests, interception and transpiration together can account for fluxes of latent heat (vaporisation) greater than the apparent available energy, a phenomenon explained by inputs of sensible heat by advection of warm air and the efficient transfer of this energy to the canopy surface accompanied by cooling of the atmosphere. Such factors are explicit in the interception/precipitation ratio proposed in the Calder & Newson (1979) annual water use model for catchments with mixed land use. This model, as with others of the genre, also allows for the fact that transpiration will be suppressed during interception events while the canopy is wet. As a result, with the exception of coniferous forests in drier climates where the increased radiation input afforded by the lower albedo of the canopy outweighs the suppression factor, forest transpiration in upland Britain is generally a little lower than grassland transpiration would be in the same location (Calder, 1977).

An earlier analysis of the Plynlimon data (Hudson, 1988) indicated that the suppression factor leads to transpiration losses from upland forests that account for a *very* small proportion of rainfall (4–7%) compared to grassland (15%), and hence that the total evaporation from upland forests is biassed towards interception, which itself accounts for 25% of rainfall at Plynlimon. However, these apparently low transpiration rates resulted from a combined 'interception site' and catchment approach from which forest transpiration is calculated as a residual. Low transpiration estimates will inevitably result if interception rates are overestimated by the plot studies, as the two must eventually add up to total catchment evaporation. The discrepancy at Plynlimon probably arose because most of the interception sites were at low altitudes, where climatic conditions are on average more conducive to high interception efficiency, with higher temperatures and vapour pressure deficits offsetting lower wind speeds. It is important to differentiate between potential and actual evaporation, as Blackie & Simpson (1993), found higher values of E_t at high altitudes in the Balquhidder catchments largely due to the dominance of wind speed effects and the lower radiation horizon on the hilltops compared to the valley bottoms.

Within the catchment black-box, these high-altitude trees are counted as integral and equal contributors to the forest covered area. However, they have been planted in thin, nutrient-poor soils which have promoted only slow growth of the trees. The trees themselves spend much of their time in conditions of low cloud, giving low temperatures, low radiation and low humidity deficits; they may therefore have lower than average transpiration rates due to the constraints of the site. No specific studies of high altitude forests have been carried out to verify this, but similar work at Balquhidder on high altitude grass (Wright & Harding, 1993) and the same flux estimated as the residual of a parallel catchment experiment in the Kirkton catchment, at Balquhidder (Blackie, 1993), have both inferred the existence of very low transpiration rates at high altitudes. It is likely, therefore, that transpiration measured in well-ventilated, low-altitude plots (Calder, 1976; 1977) will be close to the Penman E_t fraction of, say, 10–15% of rainfall, but that this will be offset within the catchment by the low rates from the high-altitude forests that cover a significant proportion of the Severn.

Given the limited sampling of spatial variation afforded by the process studies, the average transpiration rate for the forest in the Severn catchment may therefore have been underestimated by the combination method; nevertheless it will usually be lower than the grassland in the Wye and will be less than the Penman E_t value. Overall, forest evaporation would also be expected to vary more than grassland evaporation from year-to-year because of its dependence on interception and rainfall variability; it would also be more sensitive to trends and random variability in climate.

Hydrological models developed using catchment datasets such as that available from Plynlimon, in conjunction with studies that can elucidate the physical and biological processes of evaporation, will have a crucial role to play in predicting the future evaporation and streamflow changes that could result from any given land use or climate change scenario. However, the usefulness of these models will depend on the accuracy and precision with which the individual fluxes within the experimental catchments can be estimated and on the inclusion of all significant processes occurring within the catchment.

Improved Estimates of Water Balance Fluxes

The annual water balance is used to calculate actual evaporation (AE) from a catchment using integrated estimates of annual rainfall (P) and streamflow (Q):

$$AE = P - Q - \Delta S$$

where, a positive value of ΔS represents an increase in storage within the catchment over a calendar year. Over the long term, ΔS tends to become insignificantly small relative to the magnitude of integrated P and Q. In cases where storage measurements are unavailable, Hudson *et al.* (1997b) suggest that a three-year moving average of annual P – Q can be used as a surrogate for storage changes, although care must be taken in interpretation of the individual values of annual P–Q thus derived.

The networks used for the collection of precipitation, streamflow and evaporation data from the Plynlimon catchments and their subcatchments over the period 1969–1995 are among the most intensive in existence (see Hudson and Gilman, 1993) and under normal circumstances should be well capable of producing precipitation and streamflow flux estimates within the requisite levels of precision for reliable estimation of evaporation. The development of the instrumentation, network design and analytical techniques have been described in detail elsewhere (Kirby *et al.*, 1991), but manipulation and interpretation of water balance data, and particularly of the precipitation component, is under constant review and forms one of the *raisons d'être* for this reappraisal of the Plynlimon water balance.

Hudson & Gilman (1993) indicate that the random errors associated with flow measurement may be of the order ±3% and those associated with calculating areal mean precipitation of the order of ±4%. In themselves, such errors when transferred to the evaporation (P – Q) estimate, which at Plynlimon is a small number in relation to P or Q, give a likely error of ±30% in any one year. Increasing the length of the data set reduces the uncertainty in calculation of mean P – Q over the study period and, by ignoring systematic errors that affect both catchments, the *differences* between forest and grassland evaporation can be assessed with reasonable confidence. However, not all potential systematic errors affect both catchments equally; in order to test models of catchment behaviour, therefore, establishing the absolute magnitude and accuracy of the fluxes must become a priority.

PRECIPITATION NETWORKS

The Plynlimon precipitation gauge network comprises 3 monthly-read sub-networks:

- Ground level raingauges with their orifices set at and parallel to the ground slope on exposed hillsides
- Canopy level gauges with horizontal orifices in forested areas,
- Meteorological Office Mk. II standard gauges with horizontal orifices set at 30 cm above ground level, in a small number of clearings within the forest area of the Severn.

Wye rainfall is estimated from 21 ground level gauges, Severn rainfall is estimated from a combination of 11 canopy gauges and 7 ground level gauges but, in times of snow, both catchments rely on information provided by selected subsets of the network of 9 (7 pre–1979) standard gauges sited in and just outside the Severn catchment.

Precipitation measurement errors are difficult to assess because no absolute standard exists. Systematic errors due to gauge performance may differ in the Wye and Severn catchments. This is due to the different make up of the two networks: the Wye has only ground level gauges, mounted with the orifice parallel to the ground surface, while the Severn has an approximately equal mix of ground level and above canopy gauges with horizontally-mounted funnels. Unbiased estimates of absolute precipitation can be gained only if systematic errors are eliminated. The most obvious bias is due to the sloping orifice of the ground level gauge, a problem that is easily corrected by use of the factor, $1/\cos\theta$, where θ is the declination of the gauge orifice (and ground surface) from the horizontal. It is assumed that in sloping topography it is the vertical component of rainfall falling through the 'plan' area of the catchment that is important. The cosine correction increases the Wye precipitation from as-read values more than the Severn; in consequence Wye P–Q values are increased and the differences between the catchments (the 'land use effect') are reduced.

In exposed locations, standard gauges can undercatch in proportion to the wind speed at the site, with up to 30% reductions recorded in extreme conditions (Rodda & Smith, 1986; Kirby *et al.*, 1991). At Plynlimon this problem has been minimised by siting standard gauges only in existing sheltered forest clearings, thus conforming to Meteorological Office guidelines on gauge exposure. Unfortunately, this prevented deployment of standard gauges using the same stratified random sampling technique (domain theory[1]) that has been applied to both ground-level and canopy-level gauges, and resulted in a lower network density within the forested area of the Severn catchment where 3 (pre–1978) to 5 (post 1978) standard gauges sample the same area as 11 canopy gauges.

Canopy-level gauges of the type used at Plynlimon have been subject to less performance testing than other types of gauge. Nevertheless, in wind tunnel tests, the conical funnel of the gauge performs as well aerodynamically as more conventionally shielded gauges (Robinson & Rodda, 1969). A field comparison of ground level and canopy level gauges at Plynlimon (Newson & Clarke, 1976) also indicated no systematic differences between their non-snow catches in similar domains. However, the position of the gauge funnel in relation to the canopy surface is critical. The gauges in the Plynlimon catchments, mounted on vertical modular towers, can be raised to a position above the mean canopy level as the trees grow. Care has to be taken not to raise these too high into the boundary layer where there will be an increased risk of wind-induced undercatch. Funnels set too low can either undercatch or overcatch, the former problem caused by oversheltering, and the latter by drip into the funnel from surrounding branches. Over the study period such errors become obvious from plots of cumulative rainfall where changes in the behaviour of individual gauges with respect to the network mean can be used to identify exposure and other problems.

The characteristic agreement of the three networks breaks down in snow periods, as the ground level gauges overcatch due to drifting, snow-bridging and preferential melt into the funnel, while the canopy level gauges undercatch due to the limited capacity of the funnels to hold solid precipitation. As continuous data are a pre-requisite for water balance research, the only recourse at such times is to use data from the standard gauge network. An additional problem is that the storage gauges are read monthly, so data has to be infilled for the whole month even if the snow was present for only a short period. Use of the Severn standard gauges to infill during snow periods is a strategy that is clearly appropriate for the Severn, but less so for the Wye. This is not thought to be a serious problem where integrated water balances are concerned because of the small proportion of the time this method of infilling has to be used. It is certainly better than uncritical acceptance of either ground level or canopy level data during snow, an approach which could enshrine serious errors in the water balance analysis.

METHODS OF DATA CORRECTION AND INFILLING

When data are missing, infilling is necessary to prevent bias in the calculation of catchment mean precipitation. The most common reason for correction or infilling of precipitation values is snow, the occurrence of which can be identified relatively easily at Plynlimon from records kept of snow falling and lying at the Moel Cynnedd Meteorological Office climate station. Snow months present a particular problem in this respect because it is not uncommon for 39 out of the total of 48 gauges in the Plynlimon catchments, i.e. all the ground levels and canopy gauges, to have suspect or missing values. However, not all problems are caused by snow, and not every occurrence of snow causes problems.

[1] Domain theory divides each catchment into areas within four equal altitude ranges, three categories of ground slope (0–9°, 10–19°, >20°) and four aspect categories (quadrants). Individual domains representing >2% of the catchment area are allocated one raingauge, sited at random, with the gauge type dictated by vegetation cover at the site.

Individual gauges can have problems in particular months for many and varied reasons, e.g. vandalism, misreading, spillage or blockage, leaving gaps or suspect data in the monthly rainfall array. These may be easy to identify, but longer term problems that provide more difficulties can also show up. Gradual changes such as the development of small leaks can often be identified only as a long term deviation of the cumulative gauge catch from a reliable reference such as the network mean. An example is shown in Fig. 1. The cause of the deviation in the catch of Upper Wye D1Y (W18) gauge is still not known, but the clear discrepancy has led to the latter part of the record being discarded and infilled and the gauge being reinstalled.

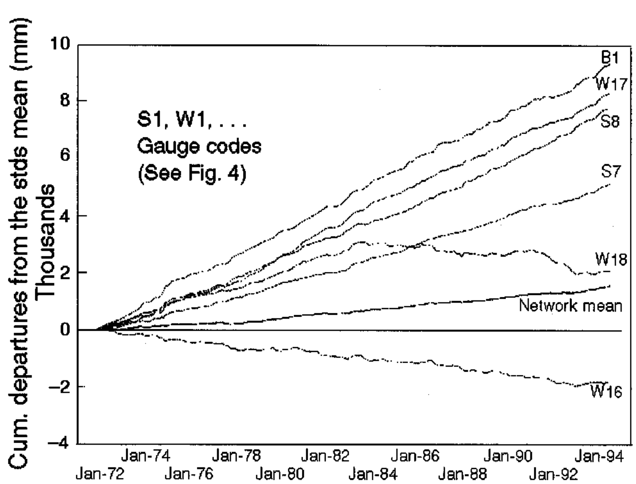

Fig. 1. *Cumulative monthly precipitation departures from the standard network mean for selected high altitude gauges in the Wye catchment, illustrating the trends and the identification of problems with individual gauges (e.g. W18).*

Identification of Snow Periods

It has been assumed that under most conditions, including snow, the small network of appropriately-sited standard gauges in the Severn (Moel Cynnedd, Blaen Hafren and Tor Glas) gives the correct point precipitation. These gauges are read daily during snow periods. Ground level and canopy level gauges are deemed 'snow-affected' when their relationship with the standard gauge network for that month deviates from the established non-snow relationship beyond a prescribed threshold (5%), and when there is corroborative evidence from the Moel Cynnedd records that snow is the likely cause. The standard gauges selected for this procedure have had to fulfil the following criteria:

- They cover the whole record for the catchment study.
- Between them they cover much of the altitude range of the catchment.
- They are not subject to regular snow drifting and are visited and maintained frequently (snow cleared and funnel contents melted) to guarantee they will be unaffected by subsequent falls of snow.
- They do not suffer from any systematic deviation from expected values due to poor exposure during either rain or snow.

Infilling of snow-affected data is feasible only if it is assumed that the spatial distribution of falling snow is roughly equivalent to that of rainfall, i.e. catches increase with altitude at the same rate during snow months as during rain-only periods.

Calculation of Site Ratios

The basic method of infilling starts with calculation of the long term ratio of each gauge catch to the mean catch of a reference network. The reference can either be the network of which the gauge is a part, or an independent network, which in the case of Plynlimon would be the standard gauges.

Iterative Method

The long term (27 year) cumulative total is calculated, using a computer spreadsheet, for each gauge in all three networks, irrespective of the existence of gaps in the data. The ratio of each gauge total to the network mean total is then calculated and used to estimate infill values for gaps in its record. This ratio is clearly not fixed, but will alter in response to up to 50 iterations of the spreadsheet, thereby incorporating infilled data and data corrected for snow into the calculated ratio and the individual monthly network means. This gives an increasingly more precise (though not necessarily more accurate) estimate of the missing gauge values.

Fixed Ratio Method Using the Main Networks

This procedure calculates gauge to network ratios using only months guaranteed not to have been affected by snow and complete in every other way. This has the disadvantage that the calculated ratios are biased towards summer and autumn rainfall patterns, when it is largely winter rainfall that needs correcting, although some winter rainfall will be included in the sample in snow-free years. The advantage is that no iteration is required and, once calculated, the ratios are fixed unless updated in future years when extra rainfall data become available.

The fixed ratios can either be calculated for the data over the whole period, or alternatively the data set can be broken down into fixed-period blocks, to allow:

- a long enough period for the calculated mean ratio to stabilise.
- for the fact that the precipitation characteristics of individual sites may undergo a 'real' change with respect to the rest of the network during the study period, so that a single ratio may not be appropriate. Ratios calculated in this way can be fixed for each block of data, one advantage being that they are not subject to updating every time the precipitation record is extended.

Fixed Ratio Method Using an Independent Network

It may also be an advantage when data for a large number of gauges are missing, e.g. during snow periods, to use as the ratio denominator an independent network of gauges that has a complete record for the month; in the case of Plynlimon this is a combination of the three most reliable standard gauges in the Severn (Moel Cynnedd, Blaen Hafren and Tor Glas). The independent ratios derived may be less precise because of the restricted information used in their calculation, but they can at least be used without bias to infill missing values throughout the whole record, and are indispensable during snow periods.

Infilling of Individual Values

The long term ratios for each missing gauge, calculated using either the iterative or one of the fixed ratio methods, can then be multiplied by the network mean for that particular month. This can be achieved in two ways:

- The *iterative* infilling process calculates the missing values progressively by updating the catchment means and also the long term ratio. There is always a risk with iterative procedures that bias will be enshrined in the infilled data due to the non-representative nature of the gauge values used to calculate the original catchment mean value; this could cause the infilled values to converge on the wrong figure (generally this will be too low).
- When the *fixed* ratio catchment network method is used, the method has to take into account the fact that the mean of the available gauge values for any particular month will be a biased estimate of the true mean. A correction therefore has to be applied to account for the deviation from unity of the mean of the long term ratios of the gauges available for that month. The problem does not arise when using the independent network method as it is ensured prior to spreadsheet analysis that the standard gauge array is complete by infilling the few missing values using an intra-network ratio method.

There are philosophical arguments for and against each infilling method proposed, but the final proof is in the comparison of results obtained. The iterative method has been shown to give very similar results to the fixed method for the whole-period ratios (<0.1% difference). In theory, the larger the sample size of months used in calculating the long term ratio, the more stable the estimate of that ratio becomes, assuming there is long term stationarity in the spatial pattern of point rainfall within the catchment.

For most gauges in the network the ratios have been found to stabilise after some 50 months and remain reasonably constant thereafter. Some exceptions are discussed in the section on spatial distribution. A full discussion of variations in stationarity is outside the scope of this paper.

After due consideration the values of individual gauge monthly totals have been taken from a combination of:

- Good data as-read.
- Missing data during snow periods infilled using the fixed long term (27 year) ratio of each gauge to the 3-gauge standard network.
- Missing data during non-snow periods infilled using the fixed long term ratio of each gauge to the 'adjusted' catchment network monthly mean.

ESTIMATION OF CATCHMENT PRECIPITATION

The completed array of monthly gauge values can now be used to calculate monthly mean catchment precipitation. If the original gauge distribution hypothesis (domain theory) is correct, and the sample size is large enough, the arithmetic mean of the gauges should give a sufficiently accurate estimate of the areal catchment rainfall. In practice, most networks are flawed in this respect and each gauge in the network does not have an equal influence on the catchment mean. Gauge catches therefore have to be weighted to take account of the proportion of the catchment each actually represents.

Domain theory was used to distribute the gauges in the first instance on the grounds of an *a priori* assessment of the likely controls on spatial distribution, and thereafter to provide a method of weighting the precipitation values areally. The Thiessen polygon method of weighting is often preferred because of its ease of use and the lack of subjectivity required in its deployment. However, the Thiessen method is independent of the original precipitation sampling distribution and, although this probably does not matter in areas of gentle topography, in upland areas it takes no account of the obvious topographic controls on rainfall that should underpin the method of interpolation of the precipitation surface between gauge sites.

A simple analysis of the mean annual catches of the three networks in the Severn catchment indicates that the spatial distribution of precipitation conforms only partially to domain theory and that the type of gauge used and regional effects may also influence the calculation of catchment precipitation.

Spatial Distribution of Precipitation

From Fig. 2, it is clear that the ground level gauges have the highest catches overall, which is not surprising considering that they occupy most of the high altitude sites; rainfall in both the Wye and Severn has long been known to vary (i.e. increase) mainly with altitude, as it does in most upland areas in Britain. The rainfall gradient is largely due to the effect of orographic uplift of the predominantly south-westerly airstream over the Plynlimon range (Kirby *et al.*, 1991), the seeder-feeder enhancement of cloud water content and condensation at high altitude, and the rain shadow that results in the lower-lying parts of the Plynlimon catchments downwind of the areas of highest rainfall.

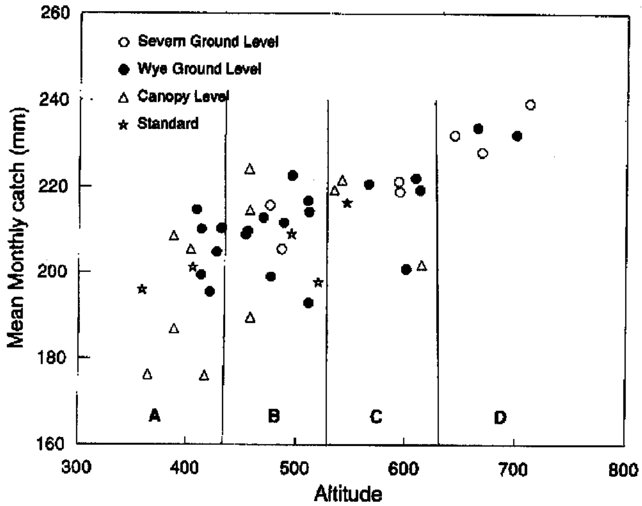

Fig. 2. *Mean monthly precipitation in the Severn and Wye catchments for different gauge networks and other altitude domains A,B,C.D used in catchment mean estimation.*

Gauge type presents no problem in the Wye because the network consists solely of ground level gauges, as does the network in the upper, non-forested parts of the Severn. However, the forested part of the Severn is covered by both canopy level and standard gauges, and a choice has to be made which network to use. The canopy gauges have a 1.4% lower mean catch than the standard gauge network and cover much the same altitude range. The standard gauge values are within the envelope of canopy gauge values in each of the three lower altitude domains (Fig. 2). This suggests a possible source of systematic error not picked up in earlier analyses that were carried out on more restricted data sets (Clarke *et al.*, 1973; Newson & Clarke, 1976). As the original network design did not include standard gauges, in a strictly statistical sense the canopy gauges are the only ones that fit the stratified random sampling technique being employed. However, the standard gauge network is a ready-made, albeit lower-density, substitute that is known to work better than canopy gauges in snow periods. Standard gauges have already been substituted for some of the canopy gauges in the network after clear-felling, as they are the only appropriate choice to suit the aerodynamics of the brash canopy left; in practice the boundaries between the networks have therefore already been blurred.

The evidence for and against the use of canopy or standard gauges is contradictory:

- In only one instance has a ground level gauge and canopy gauge been run in parallel within the same domain, at Hore C2X (S16 in Fig. 3) gauge in the upper Severn area between April 1978 and November 1979. Excluding monthly totals known to include snow (unfortunately this was one of the snowiest periods on record), the catches of the two gauges, which are sited roughly 50 m apart, were very close (<1%), indicating that even at a very windy site the canopy gauge is capable of performing equally as well as the ground level gauge; the latter is the recommended WMO reference (Sevruk & Hamon, 1984) and is in the process of being debated as the European reference gauge (BSI, 1997).

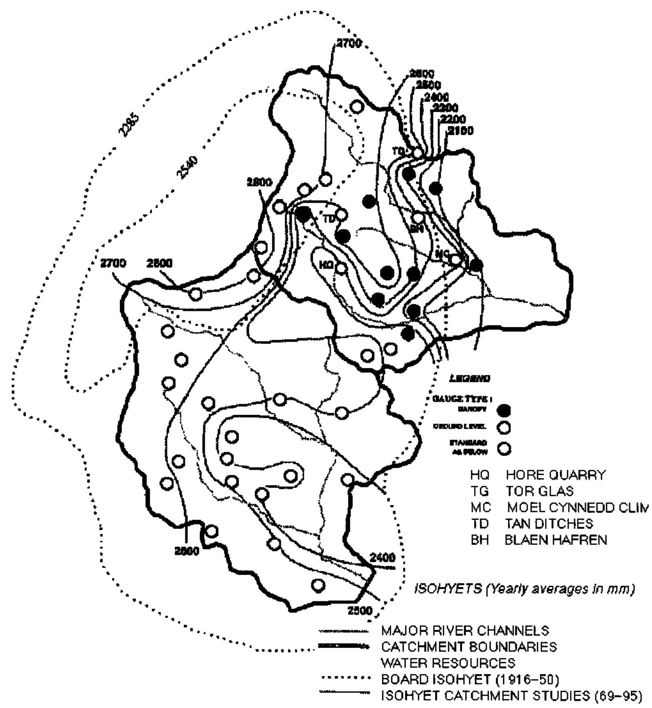

Fig. 3. *The spatial distribution of precipitation in the Plynlimon catchments from the combined networks. This is compared to the regional distribution for the 1916–50 period produced by the Water Resources Board (1967), using a lower density network but incorporating gauges from outside the Plynlimon catchments.*

- The ratios to the standard reference network of the 4 (out of 11) canopy gauges replaced by standard gauges after clear felling have all changed, but some changes have been positive and some negative. The standard gauges were sited in artificial clearings formed in the brash to conform with exposure criteria (horizon declinations). However, it is difficult to define the correct micro-exposure simply by scaling down the exposure criteria for clearings within a forest of large trees without other wind effects becoming important. Clearfelling large areas of forest may change the spatial climate distribution within the catchment, especially in terms of windspeed and direction, and may alter local micro-climates in such a way as to change the actual precipitation at individual sites. It is not surprising that differences in catch have been noted and these may have nothing to do with the types of gauges deployed.
- In aerodynamic terms, in windy conditions, evidence of undercatching by standard gauges is stronger than that for canopy level gauges. Canopy gauge performance is independent of site characteristics, unlike standard

Table 1. Estimates of Wye and Severn annual catchment average precipitation (mm) using various network combinations and methods of areal weighting for the period 1969–95

	Arithmetic Mean		Altitude Domain		Thiessen	
	R/fall	%*	R/fall	%*	R/fall	%*
WYE						
GL	2544.2	0	2540.3	–0.15	2534.3	–0.39
SEVERN						
GL + Can	2523.4	0	2498.4	–0.99	2487.2	–1.44
GL + Std	2581.1	+2.3	2523.5	0	2517.9	–0.22
GL + Can + Std	2507.1	–0.65	2493.0	–0.97	—	—

* percentage deviation from the estimate using arithmetic mean weighting and the gauge combination that includes ground level (Wye and Severn) and canopy level gauges (Severn only).

gauges where the size and exposure of the clearing sites chosen can have a marked influence (Kirby *et al.*, 1991).

Raingauge Network Distributions

Before a final decision is made on which networks to use to calculate catchment precipitation, it is necessary to look in more detail at their relative performance. Canopy level and standard gauge catches at similar altitudes can differ markedly, for reasons that have nothing to do with poor aerodynamic efficiency and everything to do with the different ways the networks were originally deployed:

- There are fewer standard gauges in the forested part of the Severn; the spatial variability in precipitation cannot therefore be sampled as comprehensively as by the canopy level gauges.
- There is a notable lack of standard gauges in the most easterly and lowest altitude portions of the Severn catchment, even though there is independent evidence from standard gauges to the north-east of the catchment, at Dolydd (308 m) and Cwm Biga (305 m) for instance (for locations see Crane and Hudson, 1997; Hudson *et al.*, 1997a), for the existence of a regional rain shadow, which may explain the low canopy level catches in this area and the rapid reduction in catch with lower altitude in this area of the catchment (Fig. 2). This area of low rainfall can also be seen in the catchment isohyetal map (Fig. 3) and is corroborated by the regional isohyetal map drawn by the Water Resources Board in 1967 (Kirby *et al.*, 1991).
- In areas of the Severn catchment where the distributions of canopy and standard gauges overlap, there appears to be no systematic direction of deviation, i.e. standard gauges can exhibit either higher or lower values than canopy level gauges.
- Canopy gauges sample rainfall on slopes, whereas the rationale behind the original deployment of the standard gauges (mainly by the Severn River Authority) was to find relatively level ground, either in the valley bottoms (Dolydd, Moel Cynnedd, Cwm Biga, Blaen Hafren) or on interfluves (Tan Ditches, Tor Glas). Only one standard gauge occupies a sloping site, Hore Quarry, and this has both a southwesterly aspect and a low catch for its altitude. This feature is shared by many of the canopy gauges in domains with similar aspects, but it is not an effect that is easy to define statistically from domain theory. It may be due to rapid uplift of air in the direction of the prevailing westerly or southwesterly wind, causing low rainfall on the lower and mid-portion of windward slopes, a feature that was also noted in the Balquhidder catchments by Johnson *et al.* (1990).

When plotted against altitude (Fig. 2), all gauges fit within a broad envelope with no obvious systematic difference between sites that can be attributed to gauge type. Any suggestion of deviating from the original ground level plus canopy level network is not supported by an analysis of network effects. In Table 1, estimates of annual rainfall have been made for the Severn from various combinations of the ground level (GL), canopy level (Can) and standard (Std) gauges, using various weighting techniques—arithmetic mean, Thiessen polygons and domain theory. A simplified domain theory has been used, resulting from the analysis of Clarke *et al.* (1973) in which altitude was shown to be the only significant domain characteristic controlling precipitation variability. The mean value of the gauges in each altitude domain (Fig. 2) is weighted by the area of the catchment in that domain.

The main feature of the analysis is that, for each network combination, the arithmetic mean always gives the highest values. The difference between weighting methods is most striking in the Severn, where the domain and Thiessen methods give values for the GL+Can network respectively 0.99% and 1.44% lower than the arithmetic mean. However, the calculation of the arithmetic mean gives an equal weighting to the highest altitude gauges when, on an areal basis, they are representative of only a small proportion of the catchment. In the Wye, where there can be no 'gauge effect', all areal estimates are within 0.4% of each other and therefore equally appropriate.

In the Severn the arithmetic mean estimate is +2.3% higher than the domain estimate by using the GL+Std network combination. This result suggests that using standard gauges in the network introduces bias because of their poor spatial distribution, but that this occurs only when using the arithmetic mean weighting. Furthermore, it can also be argued that the raw standard gauge data should be increased by a further 2% to allow for the long term undercatch relative to ground level reference gauges recorded at various sites in and around the catchments (Kirby *et al.*, 1991). However, the discrepancy between the two types of gauge is not significant (<1%) when snow is absent and has, therefore, been ignored.

The altitude domain weighted estimates on the other hand show a 'standard gauge' effect of <1%. For this water balance analysis, the altitude domain-weighted estimate has been adopted for use with the GL+Can network.

Clearly, there remains variance in rainfall in both catchments unexplained by altitude alone, and particularly in the Severn. These anomalies are probably related to the impact of regional gradients and local windward/leeward effects that are hard to quantify in an objective way, and will require future investigation.

STREAMFLOW

One of the strengths of the experimental approach taken at Plynlimon was the decision to equip the major subcatchments of the Wye and Severn with the means of measuring flow as an independent check on the main flow structures, the trapezoidal flume on the Severn and the compound Crump weir on the Wye (BSI, 1981). Thus the Gwy, Cyff and Iago in the Wye and the Hafren, Hore and Tanllwyth in the Severn, were each fitted with a special design of critical depth flume (Harrison, 1965), which is able to cope with the very special conditions in steep upland streams, with their high Froude numbers and large bedload yields. This 'nested' water balance approach allows the comparison of individual and lumped subcatchment results and has made it possible to identify systematic flow gauging errors. Although improvement of the flow record is an ongoing procedure, the main problem areas have been dealt with in some detail in Kirby *et al.* (1991). It is felt that the commitment to quality control and data infilling has resulted in flow estimates that are now complete, accurate and reliable, and also subject to internal verification.

POTENTIAL EVAPORATION

Although it was not developed specifically for upland conditions, the Penman (1948, 1949) model, derived originally from studies on short grassland in lowland Britain, is a good first approximation of the impact of climate on evaporation rates. It incorporates both an energy budget and aerodynamic approach to evaporation estimation, the former term relying on accurate measurements of radiation input, and the latter term depending on empirical relationships with humidity and wind speed. Relationships between Penman E_t and P–Q in the uplands are the logical first step towards providing a simple basis for extrapolation of water balance results to other catchments (see Calder and Newson, 1979).

Actual evaporation (interception plus transpiration) from upland grassland is generally lower than potential evaporation, and exhibits a different within-year distribution. This can be explained partly by soil moisture stress, which can be prevalent on the thin soils common in the uplands, and also by curtailment of transpiration outside the short growing season for grass in the higher altitude areas, even when atmospheric conditions are suitable for vapour transfer (Wright & Harding, 1993). Forest evaporation, on the other hand, is as dependent on low aerodynamic resistances enabling vertical mass transfer of vapour as it is on energy input. The interception process can be better described by using variations on the Penman equation (Monteith, 1965; Thom & Oliver, 1977), or by canopy water balance models (Gash & Morton, 1978; Rutter *et al.*, 1971).

In the Plynlimon catchments, two sources of climate data are available to estimate E_t.

- The longest running, most complete and most reliable in its simplicity is the daily-read Meteorological Office climatological station at Moel Cynnedd (Crane & Hudson, 1997).
- Since 1973 (reliably since 1976), automatic weather stations (AWS) installed in and around the Plynlimon catchments, in the Severn (Tanllwyth—adjacent to Moel Cynnedd, Carreg Wen), in the Wye (Cefn Brwyn, Eisteddfa Gurig) and outside the catchments but nearby (Dolydd), are also available to check on the validity of Moel Cynnedd manual E_t data.

The approach adopted for calculation of E_t throughout this paper, has been to use the available and reliable manual readings of temperature, humidity and windspeed from Moel Cynnedd, along with the integrated solar/net radiation data from the AWS (Crane & Hudson, 1997). Some periods of discontinuous data have made this difficult. For the period before the AWSs were installed, 1969–1974, 'adjusted' solar radiation records from Dolydd have been used, the adjustment justified by the consistently 6% greater values recorded by the Dolydd AWS than by Tanllwyth AWS between 1989 and the present. The only remaining problem period was in early 1975 when no solar records were available at either site, and the relationship between radiation and sunshine hours was not considered precise enough to use. A method developed by Crane & Hudson (1997), employing a solar reduction factor, was used instead.

Table 2. Relationships (ratios) between E_t values from the Moel Cynnedd manual climate station, the adjacent Tanllwyth AWS in the Severn and the AWSs at Cefn Brwyn and Eisteddfa Gurig in the Wye catchment.

Year	AWS		Manual	
	Cefn Brwyn/ Tanllwyth	Eisteddfa Gurig/ Tanllwyth	Cefn Brwyn/ Moel Cynnedd	Eisteddfa Gurig/ Moel Cynnedd
1992	1.20	1.39	1.30	1.51
1993	1.21	1.27	1.28	1.34
1994	1.44	1.22	1.35	1.14
1995	1.30	1.33	1.26	1.29
Mean	1.29	1.30	1.31	1.32
Wye Mean	1.29		1.31	

The AWS data are not complete and, until a comprehensive infilling exercise has been carried out, they will not be accurate or continuous enough to be used in isolation as annual indices of evaporative demand for the whole period. However, for a subset of data from AWS sites covering the most recent period, 1992–1995, the data recovery has been good (Crane & Hudson, 1997). The summary in Table 2 indicates that actual E_t for the Wye is likely to be 31% higher overall than Moel Cynnedd manual data. This is because the Moel Cynnedd site is in a sheltered location and at a relatively low altitude. Blackie & Simpson (1993) have already demonstrated in the Balquhidder catchments how E_t can increase with altitude, contrary to accepted wisdom at the time (Grindley, 1970); as much of the Wye and Severn catchments are at higher altitudes and experience higher wind speeds than at Moel Cynnedd, an increase in the aerodynamic term would be expected. A correction factor of this magnitude has therefore been applied to manual E_t, the effects of which can be seen in Fig. 5.

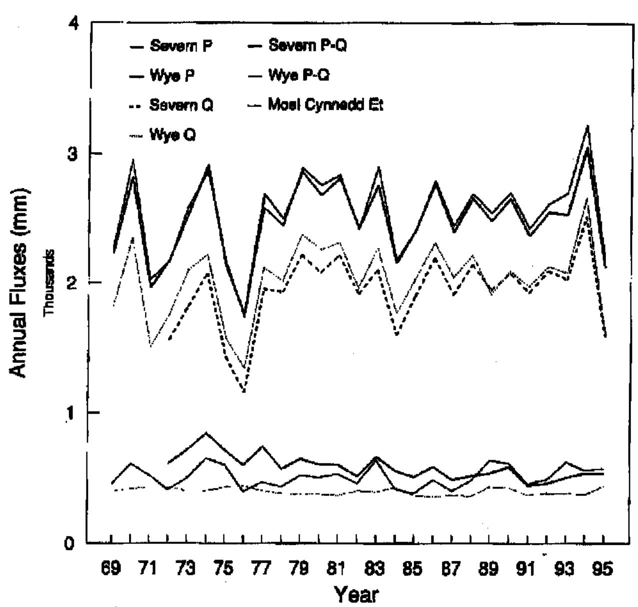

Fig. 4. *Time series of annual P, Q, P–Q and E_t for the Wye and the Severn.*

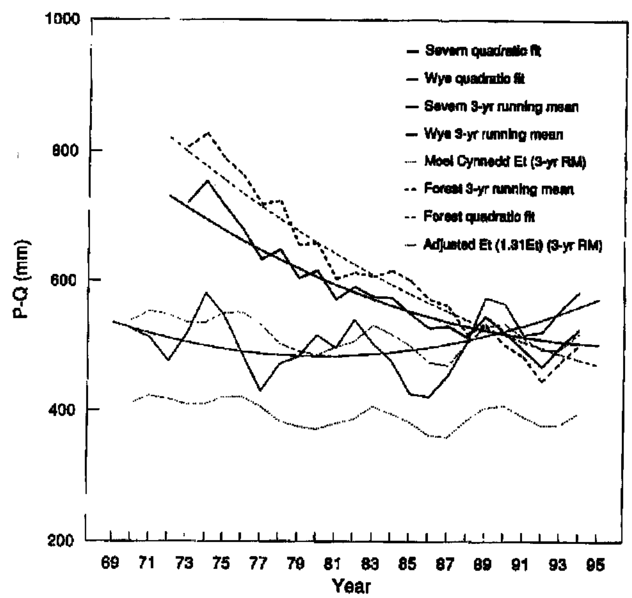

Fig. 5. *Estimates of P–Q and E_t for the Severn and Wye. Storage effects in P–Q are removed by use of the 3-yr moving average, the underlying variability in the P–Q data is characterised by quadratic curve fitting and the Severn evaporation is corrected to give forest area evaporation only. E_t is also presented as a 3-yr running mean for purposes of comparison.*

The Plynlimon Water Balance Updated

Integrated precipitation and streamflow data (P & Q) for the Wye and Severn, from which evaporation (P–Q) has

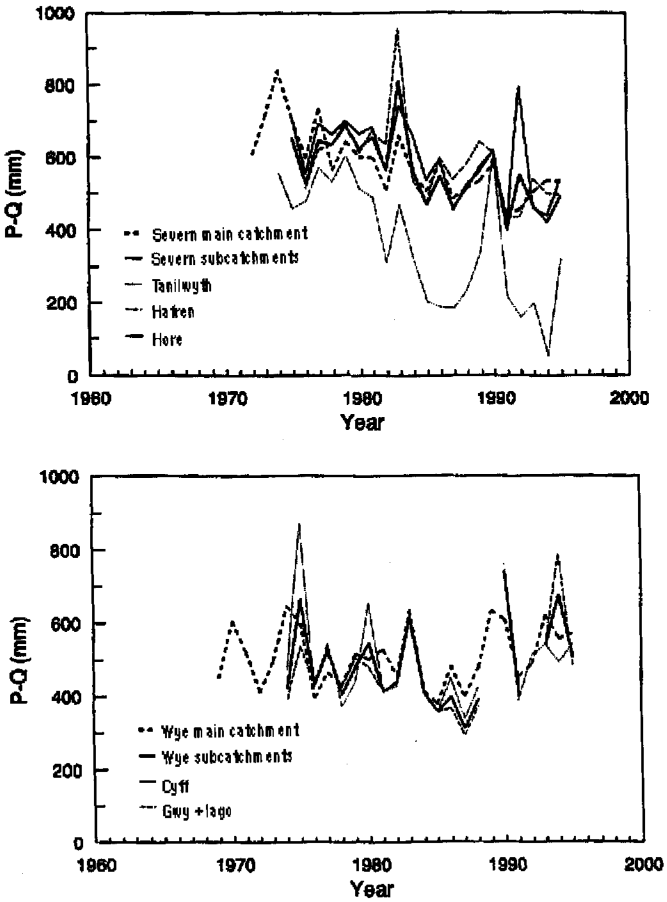

Fig. 6. *Comparison of time series of annual P–Q values for the main catchments and lumped sub-catchments in the Severn and Wye.*

been estimated, are available from 1969 and 1972 respectively, and are summarised in Table 3 and Fig. 4. Since the recent data improvements described in this paper, the flow, rainfall and potential evaporation data used in the following analysis are approaching optimal quality. Nevertheless, improving the current and historical data is an ongoing objective that must wait for long term assessment of changes in such areas as: the performance of individual raingauges with respect to the network; the effects of moving, repairing or re-installing individual gauges on their long term performance; and checks that long term discrepancies between subcatchment and main catchment water balances are not due to problems in the calibrations of any of the flow gauging structures.

RAINFALL AND FLOW STATISTICS

The annual precipitation series (Table 3 & Fig. 4) indicates considerable variability over the period. Catchment estimates are slightly higher than the 1972–1988 means quoted in Hudson & Gilman (1993), because of the revisions described in this paper. It is also noticeable in Fig. 4 that the 1977–1993 period is characterised by less year-to-year variation than in either the earliest years (1969–1976) or the most recent two years (1994–1995). The reasons for this are not clear but it does indicate the natural unpredictability of the frequency and amplitude of rainfall variations, illustrated by the annual range of 1757–3056 mm for the Severn, and 1740–3223 mm for the Wye. The extreme values occurred in 1976 and 1994 respectively in both catchments, while overall means are 2518 mm and 2556 mm in the Severn and Wye respectively. This strengthens the case for collecting data in upland catchments over a long enough period to sample fully the considerable natural variability in hydrological conditions.

Streamflow is strongly dependent on rainfall and, not surprisingly, mirrors its variation, but exhibits a steeper increase over time, particularly in the Severn catchment. This, by definition, must be caused by a compensatory decrease in evaporation. A streamflow range of 1158–2521 mm in the Severn and 1344–2665 mm in the Wye (1976 and 1994 in both cases) has been recorded; the mean for the same period as the rainfall is 1934 mm for the Severn and 2048 mm for the Wye.

ESTIMATING P–Q

Actual evaporation (P–Q) values for the Severn and Wye are also presented in Fig. 4. There is considerable annual variability, some of which must be due to storage changes over individual years. In the absence of storage estimates, either measured or estimated from soil moisture deficit models (Calder *et al.*, 1983), the method espoused by Hudson *et al.* (1997b) for the Llanbrynmair catchments has been applied; 3-year moving averages (Fig. 5) are used as a surrogate for the smoothing that would result from taking direct account of storage changes. This approach may overcompensate to some extent, but can be justified on the grounds that evaporative demand, as indexed by E_t, does not show the same annual variability as P–Q.

The comparison between the main catchments and lumped subcatchments is presented in Fig. 6 as a means of identifying possible discrepancies in estimation of the water balance fluxes. The lumped subcatchments and main catchments can never be expected to give exactly the same answer, particularly in the Wye where the lumped subcatchments account for only 76% of the area, while the comparable proportion in the Severn is 88%. However, the differences between the two types of catchment estimate are always much less than the difference between the Severn and the Wye. For the Wye, Fig. 6 indicates good agreement between both the individual and lumped subcatchments and the main catchment for most years, with some scatter caused by missing subcatchment data (see for instance 1974), which it has not yet been possible to rectify. Some doubts still surround the delineation of the boundaries between subcatchments, particularly in the Severn, and this is manifest as the poor agreement between the Tanllwyth and the main catchment. However, the

Table 3. Wye and Severn Annual Water Balances (mm).

YEAR	WYE			SEVERN			E_t
	P	Q	P–Q	P	Q	P–Q	
1969	2270	1819	451	2234			395
1970	2952	2347	605	2822			414
1971	2028	1509	519	1962			427
1972	2168	1758	410	2177	1567	610	427
1973	2598	2100	498	2535	1822	713	402
1974	2868	2222	646	2916	2075	841	399
1975	2176	1577	599	2138	1430	708	426
1976	1740	1344	396	1757	1158	599	438
1977	2584	2118	466	2691	1955	736	400
1978	2447	2017	430	2497	1932	565	380
1979	2896	2379	517	2865	2220	645	372
1980	2761	2259	502	2683	2081	602	374
1981	2842	2314	528	2816	2215	601	367
1982	2419	1961	458	2426	1915	511	399
1983	2906	2273	633	2762	2101	661	394
1984	2182	1768	414	2156	1602	554	425
1985	2406	2026	380	2404	1897	507	366
1986	2800	2316	484	2779	2194	585	354
1987	2444	2045	399	2397	1910	487	366
1988	2697	2218	479	2662	2146	516	357
1989	2546	1912	634	2485	1948	537	431
1990	2705	2095	610	2658	2076	582	425
1991	2427	1974	453	2369	1928	441	367
1992	2617	2129	488	2551	2094	457	381
1993	2702	2081	621	2534	2030	504	382
1994	3223	2665	558	3056	2521	535	371
1995	2184	1612	572	2124	1590	534	436
MEANS							
72–85	2500	2008	491	2487	1855	632	398
72–95	2556	2048	507	2518	1934	585	393

lumped subcatchment estimate agrees well, which indicates that, on summation, the large Tanllwyth discrepancy is offset by the apparently smaller discrepancy in the Hore because of the weighting effect of their relative areas. This suggests a poor delineation of their common boundary, a problem that can now be rectified numerically if not geographically. There are also minor uncertainties in the boundaries between the combined subcatchments and the ungauged lower Severn area, but the data shown in Fig. 6 indicate that no significant systematic deviation results from this.

Effects on P–Q of Different Rainfall Network and Areal Weighting Scenarios

The raingauge network analysis shows less than 3.8% range between the highest and lowest values of catchment mean rainfall derived for any given network combination. The range is bounded by the arithmetic mean estimate using the GL+Std combination and the Thiessen weighting estimates using the GL+Can combination. The altitude domain estimate, using the GL+Can combination, the method that has been adopted for water balance analysis, lies between the two. When translated to the P–Q value, the systematic error introduced in the Severn by adopting any one weighting method with the chosen network combination will be 6%, which is less than the random uncertainties involved.

Best Estimates of P–Q

After all corrections have been made, P–Q can be taken as an unbiased estimate of actual evaporation from the Severn and Wye catchments. In the Severn, P–Q averages 585 mm over the study period compared to 507 mm in the Wye. For the period before clear felling started in the

Severn, and when data are available for both catchments (1972–1985), the differences are greater with 632 mm for the Severn and 491 mm for the Wye, amounting to 25.4% and 19.6% respectively of rainfall inputs. The differences between the results obtained and those from the earlier study (Hudson & Gilman, 1993) are most obvious in the grassland Wye catchment, where there has been an apparent increase of 4% in the (P–Q)/P ratio (from 15.5 to 19.6%). This change can be attributed partly to the ground level raingauge cosine correction, even though both numerator and denominator are affected, but also to the apparent increase in P–Q in the latter half of the record as indicated by the quadratic fit in Fig. 5 (a sinusoidal fit may prove to be more appropriate than a parabola in the long term, but the record is too short as yet to define the longer term periodicity of, say, several decades). Much of this increase is due to increasing P in the Wye relative to both the Severn network and other index gauges, such as Dolydd, outside the catchments.

On average over the pre-felling period, the differences between the forested and grassland catchments do not appear to be as large as have been quoted in the past. There are two relevant factors here:

- The Severn evaporation rates have not been corrected to allow for the unforested area, which amounts to between 32 and 39% of the catchment depending on the definition of forest area used. i.e. the area under Forest Enterprise ownership or actual canopy cover. Corrected figures to simulate the effects on a 100% forest-covered catchment have been obtained by assuming that the vegetation in the ungauged, moorland upper Severn area evaporates at the same rate as the Wye. By calculating rainfall into this area from the altitude-area weighting technique, the flow from the unforested area can be estimated (Hudson, 1988). Subtracting this from the Severn flow, and using the altitude-area weighted rainfall into the forested area, allows P–Q to be estimated for the forested area from the resulting water balance. The new estimates of forest evaporation using the higher (68%) forest coverage, i.e. Forest Enterprise land, are shown in Fig. 5. This gives a higher and probably more realistic figure for the pre–1985 evaporation, which now averages 692 mm, or 28.3% of rainfall. It should be noted that the lower (100%) forest coverage of 62% would give higher values than this, so the quoted figures can be taken as a minimum forest effect.
- The difference between the Severn and Wye catchments is greater in the early years of the study than just before the planned clearfelling started in late 1985. By chance, the higher forest P–Q levels coincided with the period when the forest evaporation process studies (the 'interception' sites (Hudson, 1988) and the forest 'natural' lysimeter (Calder, 1976; 1977)) were in operation. Consequently, the agreement between the catchment results and process study predictions was closer then than for the more recent data, although even then process studies inevitably showed higher rates of evaporation. Since then the forest evaporation process appears to have changed in a way that cannot be explained by changes in atmospheric demand or water supply (rainfall) (see Fig. 7), or by the clear felling. The

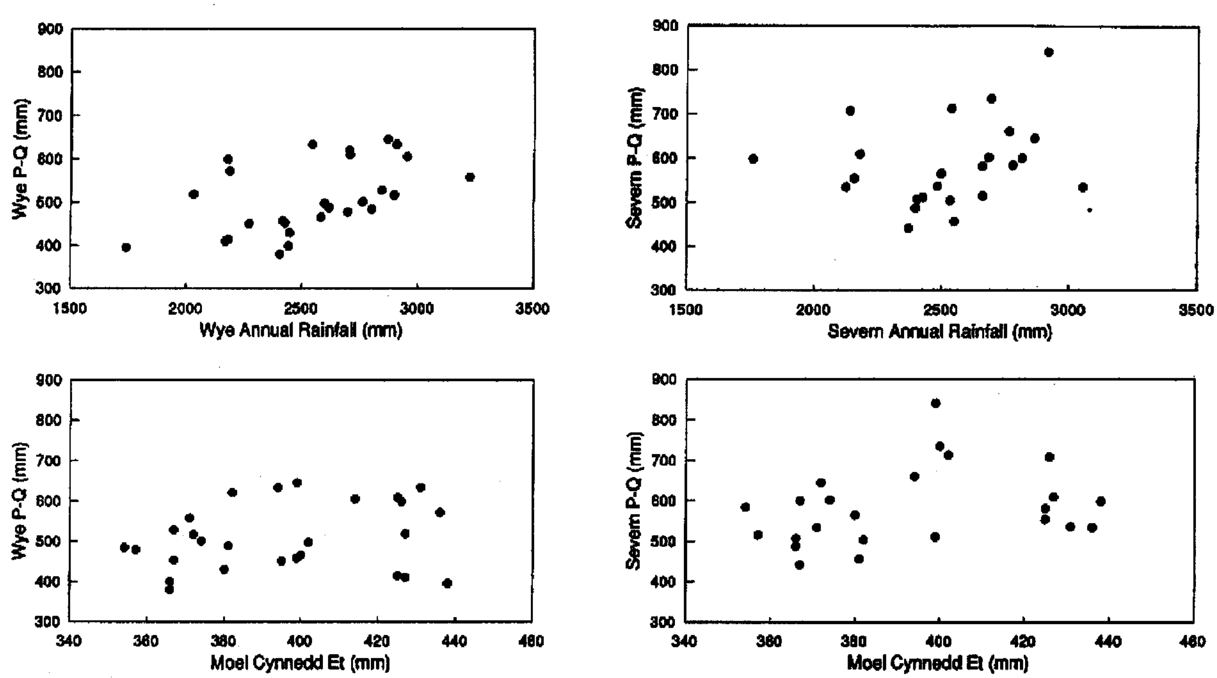

Fig. 7. *The dependence of catchment evaporation on water supply as indexed by annual rainfall and atmospheric demand as indexed by Penman E_t*

decline in Severn P–Q could either be real, due to changes in the physiological response of the trees themselves, or it could be an artefact highlighting continuing problems with the Severn data. This feature is discussed later in the paper.

Changes in P–Q with Time

Hudson & Gilman (1993) presented evidence of changes in the evaporation response of the vegetation with time in both the Severn and the Wye. The decline in Wye P–Q identified up to 1987 was not expected to continue; addition of a further 8 years of data has caused an upturn in P–Q from 1980 onwards, defined by the minimum value ($d(P-Q)/dt = 0$) of the fitted quadratic equation shown in Fig. 5. With an extended and improved dataset, much of the variation in P–Q for the Wye can now be explained by variation in atmospheric demand and annual rainfall (a surrogate for interception water supply), and not by any overall climatic trend over the study period. However, there is evidence to suggest that, since the late 1980s, increased P has coincided with, if not necessarily caused, an increase in P–Q relative to E_t.

In contrast to the Wye, there remains a clear trend in the forest P–Q, amounting to a reduction of 18.6 mm yr^{-2} or 242 mm (29.5%) over the pre-felling period (1972–1985). The least squares trend line ($r^2 = 0.73$) is significant at greater than 99.9% probability over the study period in the Severn. The decline in P–Q in the Severn which is not seen in the Wye, from forest area evaporation exceeding moorland evaporation by 60.7% in 1972, but by only 17.7% in 1985, indicates that permanent changes in the behaviour of the trees must be considered as the reason for reduced forest evaporation.

Grassland does not age, in the sense that regular grazing prevents a long term change in canopy structure, whereas forests undergo considerable changes over their growth cycle, not least in height (actual and relative), girth, leaf area and biomass. Most current process models assume that forest evaporation will increase up to a maximum at canopy closure and then stay at a rate controlled largely by atmospheric demand until felling at 40–50 years. The HYLUC model is a daily-discriminated, spatially-implicit evaporation model for mixed land use catchments, developed from process studies of interception and transpiration from individual vegetation types (e.g. from forests (Calder, 1976; 1977), from heather and shrub vegetation (Hall, 1985); from high altitude grassland (Wright & Harding, 1993) and from mixed land use utilising the annual model of Calder & Newson (1979). HYLUC was first used to attempt to explain the water balances of the Balquhidder catchments (Hall & Harding, 1993; Blackie, 1993). Initial runs of an improved version of the Calder & Newson (1979) model have been carried out on the Severn data (Price, Calder & Johnson, 1996). The output represents evaporation well in the early years, but cannot reproduce the subsequent rapid decline in P–Q. Clear felling causes some reduction in model evaporation, but not enough to reduce values to observed P–Q. The model is driven largely by E_t and will react to changes in this variable over time. However, as E_t remains relatively constant over the study period, evaporation output from the model must mirror this unless the model parameters are changed to account for clear felling.

There is strong evidence to suggest that the physiologies of plantation forest trees are not as consistent throughout the life cycle as was once assumed. Changes have been recorded in the balance of throughfall and stemflow through the forest canopy (Johnson, 1990); there is evidence of damage to fine roots, possibly due to acidification (Caspary, 1991), but possibly also due to instability in tall crops that inhabit wet and shallow soils with restricted capacity for root development; trace element deficiencies in low-fertility soils can cause forest check in later life; and reductions in the nutrient and base cation uptake of trees over 35 years old, have been identified by Stevens *et al.* (1994). All these features indicate that photosynthetic activity may decline, accompanied by lower growth rates, and suggest that varying the evaporation parameters of the land use model would be an appropriate response. However, without further research into the mechanisms of change, it is difficult to predetermine the extent of the parameter adjustments required.

It now seems possible that there is a phase of approaching senescence in British upland plantation forests that has not been fully researched, largely because few British forests have reached this stage of development. In spite of a continued healthy atmospheric demand for moisture, physiological changes may be accompanied by a decline in transpiration. The forest experiments of Calder (1976; 1977) at Plynlimon, which first explained the physics of high transpiration and interception rates recorded from 'mature' forest canopies in the uplands, and corroborated early results from the catchment experiment, took place in a block of Norway Spruce that was about 35–40 years of age at the time. Roberts (pers. comm.) suggests that:

> 'At a time when rates of transpiration from the forest on the Hore lysimeter at Plynlimon were around 300 mm yr^{-1} (Calder, 1976) the forest would, in terms measured by foresters, be growing at its highest rate. When Norway spruce forest is 30–35 years old the current annual increment (CAI) of timber volume would be at a peak and would decline steadily thereafter (Hamilton & Christie, 1971). Although it is not unreasonable to equate fluctuations in growth rate with changes in water use in a particular species at one site, the picture may not be that simple. In a complex biological structure such as a tree, growth rates may decline even though CO_2 fixation and water loss are maintained by a full and vigorous canopy. An explanation for this would be the increased respiratory demand made upon the carbon fixed by the tree as the tree becomes larger and more

complex with many more respiratory sinks. These sinks are the living tissues in branches, trunks and roots, and would compete for photosynthates with the growth zones of the tree, i.e. there would be an increase in maintenance respiration as opposed to growth respiration.'

Whether declining transpiration can explain all of the observed change requires further investigation; if it does not, the possibility of a contemporary decline in interception should also be investigated. It appears that climatic variability is not the cause, so changes in the factors implicated as the cause of high interception rates from forests, such as a smoothing of the aerodynamic roughness of the canopy in older plantations, may also play a part. Roberts proceeds:

'The vegetation characteristics controlling transpiration are the amount of foliage (leaf area index, L*) and the stomatal conductance (g_s) of the leaves. Interception losses could also be influenced to some degree by changes in L*. Unfortunately there are very few data about changes in L* and g_s over the life span of a forest. Under UK conditions it is only for Scots pine in East Anglia (Ovington, 1957) that it is has been established that L* reached a maximum at 35 years and declined thereafter. The values given by Ovington for his two oldest classes, 40 and 55 years, agree well with the value given for a 45 year old Scots pine forest at Thetford Chase, East Anglia, by Beadle *et al.* (1982). Unfortunately there are insufficient data on g_s to indicate how it changes over the forest cycle. Clearly there is a strong case for a study of changes in L* and g_s through the various growth stages of forests, both in upland catchments and also those overlying lowland aquifers.'

No repeat studies of upland forest evaporation have since been undertaken, either to cover the predominant species planted at Plynlimon, Sitka Spruce, to investigate plantations nearing 'economic' or 'environmental' maturity, or to assess the same processes in areas of higher-altitude forest subject to climatic and environmental restrictions on growth rates and transpiration and interception fluxes. The method adopted by Le Maitre *et al.* (1997) shows some promise, whereby evaporation rates can be predicted from the age of the trees in the catchment. The technique implies that evaporation rates in trees are not constant over the growth cycle, and furthermore that they depend on tree growth rates, but as yet the technique has not been applied to the type of forest exemplified at Plynlimon. The heterogeneity of upland forests must be acknowledged, and the lack of information on this topic rectified, before a fully spatially-distributed approach can be taken to modelling catchment evaporation.

RELATIONSHIP OF P–Q WITH CLIMATE

The long term ratios of P–Q to E_t represent the most basic of evaporation models that can be used to extrapolate the results from Plynlimon to other areas, and to allow prediction of the hydrological effects of coniferous forest over the whole forest rotation (Table 4).

Wye Evaporation Controls

Evaporation in the Wye is 23–29% greater than can be accounted for by the E_t at Moel Cynnedd. This is an unexpected result, as E_t is normally thought to represent an upper limit for grassland evaporation (transpiration) in any one year, with other controls such as soil moisture stress and short growing seasons often causing shortfalls of varying magnitude depending on conditions specific to each year. This suggests either that Wye P–Q has been overestimated over the whole period or, more likely, that Moel Cynnedd data underestimates E_t for the Wye catchment.

When a 31% correction is applied to E_t, as suggested in Table 2, there are far fewer years when the Wye P–Q is greater than E_t (Fig. 5), and the average P–Q is now close to average E_t (94 to 99%), the annual differences in detail being attributed mainly to storage effects. This confirms the long held belief that the Wye evaporation has been driven by transpiration from the dominant short pasture over the study period. However, the change in the relationship between P–Q and E_t since 1988 suggests a number of partial explanations which in combination could explain the apparent change overall:

- Wye precipitation appears to have increased, which will reduce the frequency of severe soil moisture deficits that limit transpiration and increase interception in areas already covered by intermediate height vegetation, e.g. heather, bilberry and rank grasses, because of the higher incidence of wet canopies.

Table 4. Relationships between catchment P–Q and evaporative demand (E_t) calculated from manual and automatic weather stations

Period	Severn		Wye	
	Manual	AWS*	Manual	AWS*
(P–Q)/Et 1972–85 (pre-felling)	1.59	1.22	1.23	0.94
(P–Q)/Et 1972–95 (whole period)	1.49	1.14	1.29	0.99

* AWS estimate refers to as-measured Moel Cynnedd E_t increased by 31% to compensate for its long term ratio with the AWSs.

- Changes in farming practices to comply with grant requirements for Environmentally Sensitive Areas (ESAs) may have reduced grazing pressures over much of the catchment; consequently, some areas of improved grassland may have reverted to shrubland or rank vegetation such as rushes and thistles. This phenomenon was identified in the Cwm catchment at Llanbrynmair (Hudson *et al.*, 1997b) on cessation of grazing prior to afforestation. There may also have been a slight but steadily increasing effect on interception loss of the small area of shelter belts (<5% of the catchment) planted in the Wye.

Whilst it is possible to use the simple long term mean ratio (P–Q)/E_t to extrapolate the Plynlimon results for both grassland and forest areas (provided E_t is also known for the ungauged area) it would improve the framework of models designed to predict forest effects in non-instrumented areas if causal links could be found between atmospheric demand and the magnitude of the Wye P–Q. In theory, if transpiration is the dominant evaporation process in the Wye, P–Q should increase with E_t. If, on the other hand, interception also contributes, as is suspected from discussion in the previous paragraph, then the supply of water to the canopy is also important.

Plotting P–Q against both E_t and rainfall individually (Fig. 7) indicates a positive but weak relationship in both cases and in both catchments (Table 5). Summer rainfall was also calculated for inclusion in the analysis but, paradoxically, was less well correlated with P–Q than was annual rainfall. However, multiple regression of P–Q on both E_t and P_W (Wye annual rainfall) improves the value of the coefficient of determination (r^2) considerably, which confirms that rather more complex feedback processes, controls and interactions are at work than can be explained by either E_t or rainfall alone. Having explained 65% of the variance in P–Q in the Wye, the remaining unexplained portion may well be hidden within the fundamental random uncertainties in estimating the water balance fluxes, due especially to the difficulties of allowing for catchment storage in the form of soil moisture, groundwater and snow. The best method of unravelling further the controls on evaporation is with a spatially distributed vegetation modelling approach, calibrated by the water balance results. The standard error of the multivariate P–Q estimate is ±10.4% which is of a similar magnitude to the uncertainty in P–Q mentioned earlier consequential on the uncertainties in estimating P and Q.

Severn Evaporation Controls

The control of P–Q in the Severn is more likely to be dominated by water supply than by atmospheric demand because of the importance of interception. However, relationships of Severn P–Q to E_t and P_S (Table 5) are weaker than for the Wye, with only 34% of the variance explained by the regression. The unexplained decline in P–Q with time, which is possibly due to physiological rather than climatic causes, is always likely to confound this issue until the relevant variable(s) or parameter(s) can be identified. Their explicit inclusion in statistical and physical models will be necessary before any improvement in prediction of evaporation rates can be achieved for the whole forest cycle.

THE EFFECTS OF LAND USE CHANGES IN THE SEVERN—CLEAR FELLING AND REPLANTING

Much of the decline observed in the P–Q for the Severn catchment is due to the removal of the tree canopy and the consequent reduction in interception. This reduction accelerated in 1985 as the planned clear felling of mature trees started in the Hore. The reduction in forest cover was of the order of 22% (15% of the Severn catchment) by 1992, by which time the total evaporation for the Severn was below that for the Wye. Although there are some signs that evaporation from the new forest, which in areas of the Hore is by now 14 years old, has started to increase once more, the Severn values remain lower than those for the Wye.

A reversal of the relative magnitude of forest and grassland evaporation is contrary to conventional opinion and

Table 5. Analysis of climatic controls on P–Q from the grassland Wye and 68% forested Severn

Controls on P–Q	Constant	Coeff. E_t	Coeff. $P_{w,s}$	r^2
Wye				
E_t (Moel Cynnedd)	131.46	0.9176	—	0.0869
P_W	199.84	—	0.1166	0.2114
E_t & P_W	−1071.12	2.4915	0.2298	0.6526
Severn				
E_t (Moel Cynnedd)	175.24	0.7817	—	0.0765
P_S	374.24	—	0.0809	0.0580
E_t & P_S	−942.49	2.4760	0.2175	0.3412

must be the result of one or a combination of the following:

- Severn rainfall, and hence P–Q, has been underestimated throughout the study period. This seems unlikely in view of the comparison of techniques discussed earlier, and the reasonable agreement between the long term Severn and Wye rainfall.
- Wye rainfall appears to be increasing relative to the Severn (Fig. 4) and also relative to gauges outside the catchment, which suggests that there have been changes in rainfall patterns over the Plynlimon range. The effect of these could exacerbate the difference in recent Wye and Severn P–Q values.
- The trees felled since 1985 had either reached or were approaching economic maturity and were therefore, by definition, the fastest-growing, most productive trees, probably due to their location on prime, low-altitude land. Over the study period, these trees had probably contributed the dominant proportion of the evaporation from the Severn catchment. Consequently, those trees that remain must be slower-growing and, arguably, less efficient in terms of evaporation, mainly due to being sited at higher altitudes where growing and climatic conditions may not be conducive to high evaporation rates. However, as mentioned previously, there is evidence from Balquhidder in the central Highlands of Scotland that extremely low rates of transpiration from high altitude grasslands may have contributed to low evaporation rates from the partially (40%) forested Kirkton catchment (Blackie, 1993). There seems no reason why these restrictions should not also apply to high-altitude forest areas, especially considering the usual similarities in transpiration rates from these crops. Even allowing for this, it is debatable whether evaporation rates from the remaining forest stands will have declined to below grassland rates.
- Areas clearfelled remain bereft of vegetation for a number of years until rank herbal species grow through the brash canopy with its higher light levels and increased availability of nutrients. During this fallow period, transpiration will be minimal, as the brash mulches the soil surface, and evaporation is sustained initially by a small amount of interception from the brash. This collapse in transpiration will be more than enough on an areal basis to offset the evaporation from the standing forest area, and to maintain low catchment evaporation rates.

In spite of the fact that the majority of trees in the Severn will be cleared over the next few years, the evaporation from the Severn is unlikely to drop much below its nadir in 1992, as each new area of clearfelling will be more than compensated by the increase in interception from the replanted forest. Data from the nearby Llanbrynmair catchments (Hudson *et al.*, 1997b) suggest that evaporation from newly planted (or re-planted) areas may increase relatively early in the life of the new crop.

Conclusions

The Plynlimon water balance has been reassessed in the light of a further 8 years of data collected since the 1969–1987 appraisal (Hudson & Gilman, 1993). Improvements have also been made to the data set, resulting from re-interpretation of up to 27 years of the rainfall, streamflow and climate data now available. The study has quantified at the catchment scale the differences in hydrological behaviour between plantation coniferous forestry and the traditional pasture it has replaced, over the forest cycle from trees of 35–40 years of age, to felling and the start of the second forest rotation. The differences between forest and grassland evaporation rates have been shown to change over time, as a result of forest growth and ageing and major land use changes such as clear felling and replanting.

Estimates of rainfall for both the Severn and the Wye have been improved by applying snow corrections and by the logical decision to correct ground level gauges for their sloping orifices. Different approaches to calculating catchment rainfall, using various networks of gauges and different methods of network weighting, do not give significantly different values of P–Q for the Severn, which justifies the investment in dense, spatially distributed and multi-type raingauge networks in the first place. A strong case has been made for using the original combined ground level (angle corrected) and canopy level gauge network in the Severn, rather than involving the standard gauge network at any time other than during snow periods.

The decline in evaporation from the Wye between 1969 and 1987, identified by Hudson & Gilman (1993) but not wholly explained, has become less pronounced in the extended and improved data set. One reason is the currently better treatment of precipitation at times of snow; this affects the early data in particular, but there appears to be a real upturn in P–Q that has also contributed to a flattening in the observed trend and justifies the assertion in Hudson & Gilman (1993) that evaporation in the Wye was unlikely to decline further and would probably rise as part of a climatic cycle. A steep decline in P–Q is still evident in the Severn, however, even before the start of clear felling; on average it amounts to 18.6 mm for each year of record (29.5% overall). This cannot be explained by changes in atmospheric demand (indexed by Moel Cynnedd E_t), or by rainfall variability over the period. Runs of the land use evaporation model HYLUC, assuming no change in the canopy parameters over the mature phase, cannot reproduce the observed decline in Severn P–Q. It appears, therefore, that there are other controls linked to the more dynamic changes in tree physiology and vegetation canopy structure in the Severn compared to the more static land use in the Wye.

The differences between 100% forest-covered and grassland areas were clearly larger at the beginning of the study (1972) when evaporation from the forest area in the

Severn exceeded the Wye by 60.7%. During this period there was good agreement between the catchment results and contemporary process studies, even though the process studies' results may have been biased upwards by the freely-transpiring and intercepting nature of the forest blocks being studied. However, by 1985, even before managed clearfelling had started in the Hore subcatchment, this difference had dropped to 17.7%. The onset of clearfelling reduced the Severn rate to less than the Wye for a few years, due to very low evaporation (transpiration) from the fallow areas, and to the fact that much of the remaining forest is at higher altitudes where forest growth is slower and evaporation efficiency much reduced. The differences are also enhanced by an apparent relative increase in Wye P, and P–Q, in the most recent years.

The Plynlimon data have made it possible to develop and calibrate simple models, requiring little data input apart from annual rainfall and Penman E_t, that will allow extrapolation of this complex set of results to ungauged catchments where land use change to forestry is planned. They will in future also provide the framework for more sophisticated models that require long runs of intensively measured hydrological variables. The close agreement between Wye P–Q and predicted model values suggests that the water balance data are sufficiently precise and accurate for the purposes of calibrating simple statistical models of moorland evaporation which can take into account climatic variability. In non-stable conditions, such as those causing a decline in Severn evaporation unrelated to climate variability, this approach meets with limited success; clearly, the interactive physiological and climatic factors must be identified and incorporated in these predictive models. Further process investigations are necessary, preferably in the Severn catchment, on the dominant species, Sitka Spruce, on trees in high-altitude climatic conditions, and on older trees than those in areas already studied.

Early results from the Plynlimon experiment justified the concern of the water industry in Britain that afforestation and water supply may be incompatible in areas where demand is high relative to available resources. The more recent results presented here suggest that the forest does not maintain its highest rates of evaporation throughout the growth cycle, taking some years to reach maximum rates and then declining as the trees approach their economic zenith. For short periods, during and after clearfelling, water resources from forested catchments may even be greater than from equivalent areas of moorland.

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